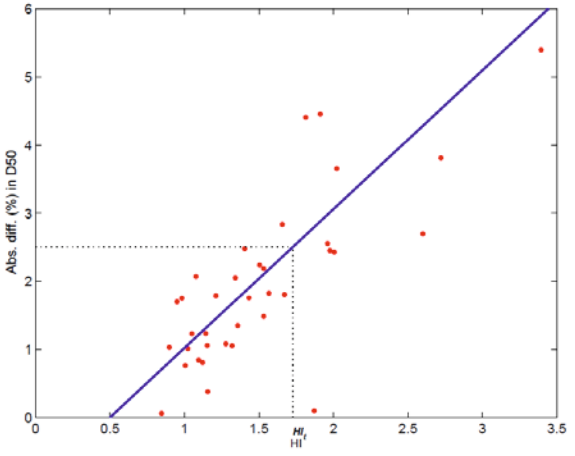
Materials and Methods: Fourteen patients treated atour facility with passively scattered proton beams were selected. Aperture areas ranged from ~3 to ~35 cm^2. Aperture sizes < 3 cm^2 were not considered in this study because aperture scattering effects might outweigh effects from patient heterogeneities. Dose distributions predicted by our pencil beam (PB) algorithm were verified against MC dose calculations using TOPAS—a TOol for PArticle Simulation layered on top of GEANT4. Open field dosimetry was corrected based on the clinical guidelines for small fields to consider aperture scattering and dose equilibrium. DVHs were analyzed and differences in the dose to the 50% of the GTV (D50) were assessed on a field-by-field basis. We developed a simple and fast methodology to quantify the tissue inhomogeneity traversed by a single beam using a heterogeneity index (HI). The implementation was based on the dose calculation approach taken by our PB algorithm. Finally, we evaluated the potential correlation between the errors made by our PB algorithm in D50 for each field and the level of tissue heterogeneity traversed by the proton beam given by HI.
Results: Discrepancies up to 5.4% were found in D50 ($[D50_{PB}—D50_{MC}]/D50_{MC}$). The discrepancies found for each field exhibited a strong correlation to their associated HI-values (Spearman's ρ = 0.8, p <0.0001); the higher the level of tissue heterogeneities for a particular field, the larger the dosimetric error by the analytical algorithm. With the established correlation a threshold for HI could be set by choosing a tolerance level; requiring an absolute difference for D50 < 2.5% for clinical routines suggests recalculation ofpatient treatments for HI_t >> 1.7.



Conclusions: The HI as defined in this study appeared to be a good indicator for theaccuracy of proton field delivery in terms of GTV prescription dose coverage. Each HI-value was obtained in less than 3 minutes allowing the implementation of this methodology in the clinical routine. For HI-values exceeding the threshold, either a change in beam direction (if feasible) or a recalculationof the dose with Monte Carlo would be highly recommended.

OC-0438
Experimental validation of monte carlo pencil beam scanning model in heterogeneous media for proton therapy.
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Purpose/Objective: To validate experimentally a GATE/GEANT4-based(G4) Monte Carlo (MC) model in heterogeneous media for dedicated pencil beam scanning in proton therapy. Comparisons between measurements and MC simulations using G4 and PENELOPE-proton are presented. A comparison against analytical modeling from commercial TPS is also investigated. This work evaluates the impact of heterogeneities on range prediction, beam shape and depth dose changes.
Materials and Methods: The MC model for pencil beam based on G4 has been validated in water and PMMA phantoms (Grevillot et al Phys. Med. Biol.(2011)) reproducing pristine Bragg peaks for a series of individual energies (from 100 to 226.7 MeV) with 0.7 mm range and 0.2 mm spot size accuracy. The same optical model was implemented in PENELOPE-proton. In order to validate the beam model in heterogeneous media, phantoms made of stacked slabs with different densities and known compositions were used. Two experimental test cases including solid water (SW), lung (LN-300) and bone (SB3) tissue-equivalent material were investigated. Depth-dose distributions for a monoenergetic single spot and 10x10cm^2 composite fields were measured using Gafchromic EBT3 films and the ionization chamber (IC) PPC05 in all configurations. To measure accurately the Bragg peak position, a stack of films of 2x2cm^2 was inserted in the last centimeter of the proton range.
Results: Figure 1 shows results for one heterogeneous configuration. All doses-to-medium were converted to dose to water using stopping power ratios. Dose distributions were arbitrarily normalized in the middle of the second SW region. Bragg peak positions are reproduced by MC simulations within 1mm in both configurations (Table 1). IC measurements, G4 (binary-cascade) and PENELOPE-proton simulations are within 2%/2 mm. Point-to-point mean difference of 1.2% is observed between G4 (precompound) and measurement in the first 15 cm of the phantom and increased to 7.2% after bone insert until 286.5mm depth. In lung and bone slabs, EBT3 films and G4 binary-cascade are inagreement within 0.77% while a mean point-to-point difference up to 1.26% is observed with G4 precompound model. The uncertainty (1σ) on EBT3 films was evaluated to be at 2.75% which included readout process and dose calibration against IC (TRS-398). A statistical uncertainty of 0.1% was achieved for MC simulations.

	Bragg peak position (cm)	
	Lung inserts	Lung and Bone inserts
IC	-	28.9 ± 0.1
EBT3	26.41 ± 0.0288	28.882 ± 0.0288
G4	26.5 ± 0.1	28.9 ± 0.1
PENELOPE-proton	26.5± 0.1	29.0 ± 0.1

Table 1. Measured and simulated Bragg peak position in two heterogeneous phantoms.

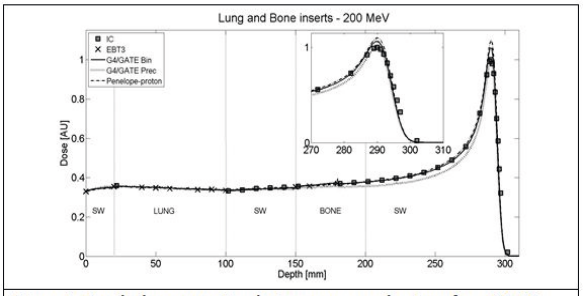

Figure 1. Depth-dose curve in a heterogeneous phantom for a 10x10 homogeneous field in a 200 MeV proton beam. IC (stars) and EBT3 (diamonds) are in agreement within 1% using G4 binary-cascade (solid line), 1.2% using G4 precompound (dotted line) simulations and 0.9% using Penelope-proton code (dashed line) until 286.5 mm depth.

Conclusions: The Bragg peak position is predicted with 1mm precision for all MC simulations, even though ionization potential values for phantom slabs were calculated using classical additive rules. G4/GATE beam model reproduce depth-dose behavior of proton transport regarding both IC and EBT3 measurement in heterogeneities.
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OC-0439
Proton dose calculation using the macro Monte Carlo method
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Purpose/Objective: Currently, pencil beam dose calculation algorithms are commonly used in treatment planning for radiotherapy with protons. These algorithms are of limited accuracy in some situations such as patient heterogeneities, which could be overcome when using Monte Carlo (MC) methods. However, MC suffers from long

computation time. Thus, in order to gain efficiency, a new macro MC (MMC) method for proton dose calculations has been developed.
Materials and Methods: The MMC transport is based on a local to global MC approach. For the local simulations GEANT4 has been used. These simulations consist of mono-energetic proton pencil beams impinging perpendicularly on slabs of different materials (water, air, lung, adipose, muscle, spongiosa, cortical bone) as well as of different thicknesses. During the local simulation the physical characteristics such as lateral displacement, direction distribution and energy loss have been scored for primary and secondary particles. Thereby multiple scattering, ionization as well as elastic and inelastic interactions have been taken into account. The scored data from appropriate slabs is then used for the MMC particle transport in the global simulation. During this simulation, the energy loss along the path between entrance and exit positions of the selected slab is calculated. Additionally, the radiation transport of neutrons, also based on local simulations, as well as the secondary ions are included into the MMC transport for the dose calculations. In order to validate the MMC transport, calculated dose distributions using GEANT4 and the MMC transport have been compared. For this purpose, dose distributions for different mono-energetic proton beams impinging on different phantoms including homogeneous and inhomogeneous situations as well as on a patient CT data set have been calculated.
Results: For the calculated integral depth dose curves the agreement is better than 1% or 1 mm for all pencil beams and phantoms considered. For the dose profiles the agreement is within 1% or 1 mm in all phantoms for all energies and depths. The same level of agreement is found for the depth dose curves and profiles using a broad incident proton beam on the phantoms. The comparison of the dose distribution calculated using either GEANT4 or MMC in the patient also shows an agreement of within 1% or 1 mm. The efficiency of MMC is up to 200 times higher than for GEANT4.
Conclusions: The agreement found in the comparisons of the calculated dose distributions demonstrates that the newly developed MMC transport for proton beams is suitable for very accurate and efficient dose calculations. In future, the MMC transport will be coupled with a beam model in order to allow treatment planning for radiotherapy with proton beams. This work was supported by Varian Medical Systems.

OC-0440
Modeling of continuous patient deformation using Monte Carlo simulation
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Purpose/Objective: A key challenge of dynamic radiotherapy treatment techniques is the difficulty of incorporating intra-fraction organ deformation in the dose calculation algorithms to generate more accurate and realistic dose distributions. The aim of this study is to use Monte Carlo simulation methods to calculate realistic dose distributions that include both the continuous deformation of organs and the continuous motion of treatment machine components for volumetric modulated arc therapy and helical tomotherapy treatments.
Materials and Methods: We have developed a 4D Monte Carlo-based calculation method capable of simulating a wide variety of treatment techniques without the need to resort to discretisation approximations. The method includes full accelerator head simulation of TomoTherapy and Elekta accelerators and a realistic representation of continuous deformation of organs and continuous motion of treatment machine components. This is done via the interactive sampling of geometry parameters using a random time variable associated to each simulated particle. We have previously presented a method to model the continuous motion of treatment machine components. In this study, the DOSXYZnrc user code was further modified to account for the continuous intra-fraction deformation of patient geometry. More specifically, we have implemented two methods to update the transport grid densities as a function of time and two methods to map the energy deposited in the time dependant transport grid back to a reference grid.
Results: The density mapping method to update the transport grid densities as a function of time was found to be superior to the density interpolation method when the patient motion is much greater than the voxel size. The voxel average method to map the energy deposited in the time dependent transport grid back to a reference grid was found to be superior to the voxel center method but requires the appropriate use of energy/mass corrections factors. Verification with a mathematical phantom and measurements with a moving phantom show that the methods were appropriately implemented in the EGSnrc user codes.
Conclusions: We have developed a 4D Monte Carlo-based calculation method that successfully models continuous deformation of organs and continuous motion of machine components.

PROFFERED PAPERS: RTT 5: IMAGE GUIDED RADIOTHERAPY: CURRENT PERSPECTIVES

OC-0441
Introduction of a fast 4D PET/CT protocol for radiotherapy planning ñ a multidisciplinary approach
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Purpose/Objective: Breathing motion induces artifacts in 3D PET that lower the geometric and quantitative accuracy required for treatment planning. On the other hand, acquisition of 4D PET typically takes much more time. Our purpose was to implement a fast protocol for 4D PET/CT acquisition for radiotherapy treatment planning of lung tumors.
Materials and Methods: Radiotherapy technologists (RTT) and nuclear medicine technologists (NMT) closely collaborated to develop the clinical protocol described below. The RTT is responsible for patient positioning and 4D reconstruction of the data, whereas the NMT is responsible for the PET/CT acquisition and 3D reconstruction.
Patients were scanned in treatment position on a flat table top with arm and knee support on a Philips PET/CT scanner. An air bellows belt (Mayo Clinic) was placed around the upper abdomen to register the respiratory signal. The acquisition protocol consisted of 1) a whole body 3D CT, 2) a fast whole body 4D PET with a 2 min scan time per bed position, identical to our standard 3D PET protocol and 3) a 4D CT of the thorax. The PET scan is reconstructed in 4D using the 4D CT for attenuation correction for the thorax region; and a regular 3D PET is reconstructed from the same data for the whole body scan.
The 4D PET is subsequently motion compensated (MC). To that end, first the patient specific motion pattern is derived from the 4D CT using deformable image registration. Subsequently, the deformation is compensated in all phases of the 4D PET scan. Finally, summing all phase bins results in a 3D MC PET. We determined the SUV_{max} value in the tumor and the size of the dominant tumor region, i.e. the region enclosed by the 50% SUV_{max} region.
To clinically validate this novel protocol, 20 lung cancer patients were included in a feasibility study. Both the logistics and image quality were evaluated.
Results: During protocol development, RTTs became aware of the proper handling of a radioactive patient, the importance of instructing patients before FDG administration and in keeping a distance whenever possible. NMT became aware of the importance of proper patient positioning and respiratory monitoring systems.
The novel 4D-PET/CT procedure took 6 (± 3) min more than a regular 3D PET/CT acquisition. This is 15-30 min less than a standard 4D PET/CT procedure. Compared to 3D PET images (figure 1b) and the single phase images (1a), the MC PET images (1c) provided better contrast and sharper images. Higher maximum SUV values (up to 25%) were detected in the tumor (mean increase 5.44% (SD=7.16)) and the apparent size of the tumor was up to 46% smaller (mean 5.47% (SD=9.67)).
Conclusions: A multidisciplinary approach in protocol development and image acquisition is essential to derive safe and efficient workflows. Our novel 4D PET/CT acquisition protocol saves 15-30 minutes acquisition time and improved PET image quality. This approach can also be implemented for other organs affected by respiratory movements such as the liver.